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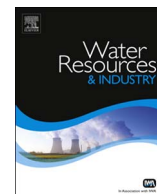
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# The blue and grey water footprint of construction materials: Steel, cement and glass

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## ABSTRACT

Numerous studies have been published on water footprints (WFs) of agricultural products, but much less on WFs of industrial products. The latter are often composed of various basic materials. Already the basic materials follow from a chain of processes, each with its specific water consumption (blue WF) and pollution (grey WF). We assess blue and grey WFs of five construction materials: chromium-nickel unalloyed steel, unalloyed steel, Portland cement (CEM I), Portland composite cement (CEM II/B) and soda-lime glass. Blue and grey WFs are added up along production chains, following life cycle inventory and WF accounting procedures. Steel, cement and glass have WFs dominated by grey WFs, that are 20–220 times larger than the blue WFs. For steel, critical pollutants are cadmium, copper and mercury; for cement, these are mercury or cadmium; for glass, suspended solids. Blue WFs of steel, cement and glass are mostly related to electricity use.

## 1. Introduction

Societies depend on freshwater for drinking, washing and cleaning and for the production of food, materials and energy. It is expected that between 2000 and 2050, global water abstractions from groundwater and surface water will increase by 55%, particularly due to a growing water demand from manufacturing and thermal electricity generation [32]. This will lead to unsustainable conditions in places where water is scarce and poorly managed [40]. Already today, 3.3 billion people live in areas that experience severe water scarcity during at least a quarter per year [28]. Human impacts on freshwater systems can ultimately be linked to human consumption, and water shortages and pollution can be better understood and addressed by considering water use along production and supply chains [15]. While it is still most common to consider only the direct water use by households, farmers, manufacturers or other water users, it is insightful to know water use of final products by summing up the water use in all steps of the supply chain, which enables an analysis of which steps contribute most to the overall water use in the production of a product. This enables further focus on how water use can best be reduced in the most critical steps of a supply chain.

The majority of previous studies to quantify the water use and pollution along the supply chain of specific products focussed on crop and animal products, which are responsible for the largest amount of water consumption in the world. The industrial sector is the second largest water user, but product-specific studies are still very scarce [16]. Steel, cement and glass, the focus of the current study, are construction materials produced in millions of tonnes globally per year [31,37,46]. In the production chain of steel, cement and glass, water is needed and polluted in several processes. Besides, water is required indirectly for producing the energy applied in

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the production chain. For example, electricity produced in a power plant and used to mine iron ore needs cooling water. In the production chain of construction materials, emissions of toxic substances cause water pollution. The water footprint of these materials is potentially large, but never quantified before. In general, steel, cement and glass industries do not consider their supply chain water use and limit their scope to their own operations. For example, the water reporting and accounting guidelines from the Cement Sustainability Initiative excludes the supply chain [42,43].

The objective of this research is to assess the blue and grey water footprint (WF) of the most commonly used types of steel, cement and glass in terms of water volume per unit of mass of the end product. The blue WF refers to the consumption of fresh groundwater or fresh surface water; the grey WF refers to the volume of freshwater required to assimilate pollutants discharged into freshwater bodies [18]. The following research questions are addressed: what is the blue WF of the most commonly produced types of steel, cement and flat glass, produced by the most commonly used production routes; what is the grey WF of these products, accounting for different types of pollutants; which processes give the largest contribution to the WFs of steel, cement and glass; and which substances determine the grey WF of steel, cement and glass? Since steel, cement and glass are basic construction materials, the results of this study will be helpful in water footprint assessments for infrastructure or products containing these materials.

The study is based on the accounting procedures as commonly employed in Life Cycle Assessment and following the Global Water Footprint Standard published by Water Footprint Network [18]. This paper is the first study that employs commonly used LCA software and databases to estimate the blue and grey WF of steel, cement and glass. While Life Cycle Assessment (LCA) and Water Footprint Assessment (WFA) have different roots, the current study shows that methods and tools from both fields can effectively be combined. The LCA research field focusses on the quantification of potential environmental impacts of products considering a range of environmental issues (e.g. climate change, emissions of pollutants). To do this, first an inventory is made of all processes in a production chain. Advanced software programmes like GaBi [13] and databases like Ecoinvent [7] have been developed to support the execution of LCA studies. The interest in applying LCA to water started to develop in 2009 [30], and in response to that water use has been better incorporated in the LCA databases. WFA is a research field that has evolved since 2002 to address the relation between the consumption of goods and services on the one hand and water use, scarcity and pollution on the other. It is based on four notions [17]. First, freshwater is a global resource, because people in one place use freshwater resources elsewhere. The constituents for construction materials, for example, are mined all over the world, transported, produced and then distributed again. The second notion is that freshwater renewal rates are limited: over a certain period of time, precipitation in an area, recharging groundwater and river flows, is always limited to a certain amount, putting a constraint to water consumption. If freshwater is consumed for the production of construction materials, it cannot be applied anymore for other purposes, hence the interest in where precisely scarce water resources are used for. The third notion is that to understand the impacts of water consumption, we need to consider complete production chains. The fourth notion is that we need to consider both water consumption and water pollution. LCA and WFA serve different purposes, but the inventory stage of LCA and accounting stage of WFA require the same sort of supply chain analysis and data [3]. The current study is innovative in showing how blue and grey WFs can be estimated employing LCA software and databases.

## 2. Production chains of steel, cement and glass

### 2.1. Steel

Iron and steel have played an important role in the development of human civilisation. In the 13th century BC, steel was first produced and the Iron Age began [45]. In modern society, iron and steel have many applications, such as for construction, the automotive industry, for tools and machinery. The construction industry is the largest steel using industry, accounting for more than 50% of the world steel production. In 2015, the total world steel production was 1622.8 Mt [46]. Steel is a product derived from iron with a small carbon content that is used for iron production. When other metals are added to steel, so termed alloys are produced. Stainless steel is an alloy that includes chromium, nickel and manganese. The majority of steel is unalloyed steel, also called carbon steel. Of the worldwide steel production, 89% is unalloyed steel and 11% is alloyed steel [38].

There are several steel production routes. The most common is the blast furnace (BF) / basic oxygen furnace (BOF) route. The BF is a furnace where oxygen is removed from iron ore by binding it to carbon. The BOF is a furnace where the carbon content in the iron is lowered by blowing pure oxygen onto the metal. In 2014, the BF/BOF route produces 74% of total steel [44]. Fig. 1 shows the six steps of the steel production chain: (1) mining of raw materials; (2) processing of raw materials (beneficiation, calcination and coking); (3) iron ore reduction; (4) air separation; (5) ferroalloy production and (5) steel production. Every step needs the input of energy (red arrows) and water (blue arrows) and results in the output of products (black arrows).

In the first step, the raw materials, mainly consisting of iron ore, limestone ( $\text{CaCO}_3$ ), dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ), coal and other ores for alloyed steel, such as chromite and laterite, are mined. In the second step, the properties of the raw materials are improved by the following processes:

- a. Beneficiation, the process where the ore concentration is increased and fine ore particles are bound to form pellets or sinter. Fine coke is the main energy source for sinter production [35]. Water is used for dust emission control, sorting material, cleaning, cooling and gas treatment [41].
- b. Calcination, the process to produce lime ( $\text{CaO}$ ) and calcined dolomite ( $\text{CaO.MgO}$ ) from limestone ( $\text{CaCO}_3$ ) and dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ). Lime and dolomite remove impurities from steel [2]. Sometimes water is used to wash limestone. Mostly gas and solid fossil fuels are used for calcination [37].
- c. Coking, the process that improves coal properties. Coal enters a coke oven resulting in cokes. Cokes have a higher carbon purity

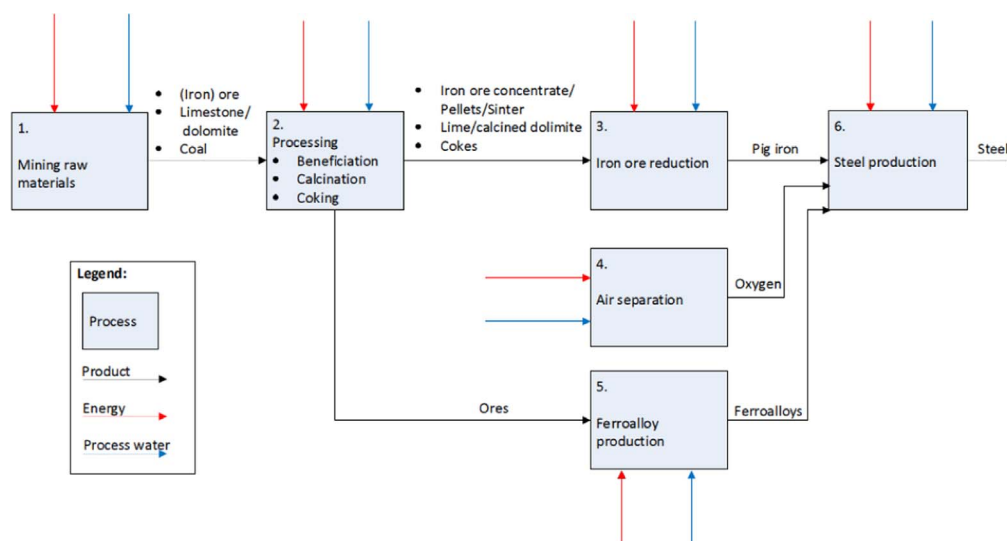


Fig. 1. The steel production chain including six steps: (1) mining of raw materials; (2) processing of raw materials (beneficiation, calcination, and coking); (3) iron ore reduction; (4) air separation; (5) ferroalloy production; and (6) steel production. Every step needs the input of energy (red arrows) and water (blue arrows) and results in the output of products (black arrows). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

than coal and are strong enough to carry the other materials inside the blast furnace. Water is used for wet quenching of the cokes [35].

In the third step, iron ore, cokes and limestone are put in the blast furnace to form pig iron, reduced iron oxide. Iron ore oxide binds to carbon from cokes, emitting carbon oxide, forming pig iron, a hot metal. The limestone acts as a slag former, removing iron impurities, forming BF slag as a by-product [35]. Water is used for blast furnace gas treatment, slag granulation and cooling [35].

In the fourth step, air separation, oxygen for steel production in the BOF is produced by separating oxygen from the air [1]. By blowing pure oxygen over the hot metal, the metal carbon content is lowered. Water is used for cooling and electricity provides the energy required for air separation [1].

Ferrochrome and ferronickel are the major alloys used for stainless steel production. The fifth step, the production of alloyed steel, a mix of iron and other metals is added to the basic oxygen furnace. The production of ferroalloys generally requires large amounts of electricity. Water is used for gas treatment, slag granulation and cooling [27].

In the sixth step of steel production, the pig iron from the iron ore reduction process (step 3), which contains approximately 4% carbon, is transported to the BOF where the carbon content is reduced by blowing pure oxygen onto the hot metal, forming steel. Slag formers, such as lime, are used to remove impurities from the steel, forming BOF slag [35]. Water is used for BOF gas treatment, vacuum generation, cooling and washing [35].

## 2.2. Cement

Cement is an inorganic material that binds other materials, like sand or gravel, together. It is a hydraulic binder, which means that water is needed for the chemical reactions in order to harden. Concrete is a mixture of cement, water, sand and other aggregates, such as gravel or crushed stone. The world cement production has grown steadily, especially in developing countries. In 2006, world

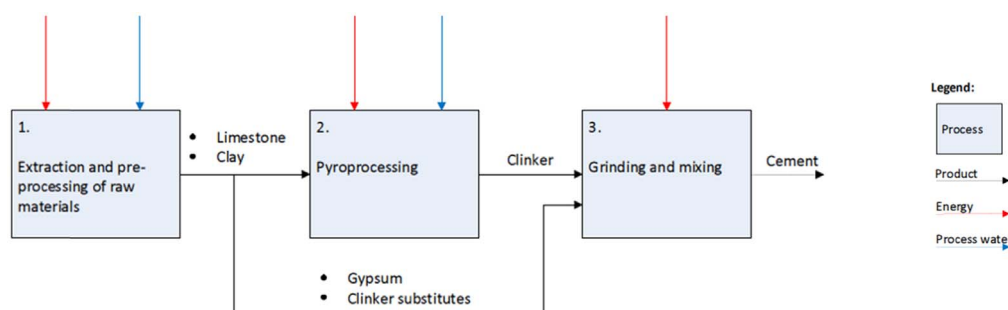


Fig. 2. The cement production chain. Every step needs the input of energy (red arrows) and water (blue arrows) and results in the output of products (black arrows). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

production was 2540 Mt [37]. Every year, more than 10,000 Mt of concrete is produced [29]. Fig. 2 shows the cement production chain, which includes three main steps: (1) extraction and pre-processing of raw materials; (2) pyroprocessing; and (3) grinding and mixing.

The raw materials needed to produce cement are limestone, or other  $\text{CaCO}_3$  containing materials, sand, clay and gypsum. These materials are extracted from quarries. Gypsum is also a by-product from flue gas desulphurisation, a cleaning process in coal-fired power plants. Other waste products can also be used, for example, ground granulated blast furnace slag, a waste product from iron and steel production. Fly ash is another waste product that is often used. It is produced from electrostatic precipitation of coal flue gas. After extraction, limestone is ground and washed to prepare for pyroprocessing, the process of producing clinker from limestone and clay. By using high temperatures in a rotating oven, limestone and clay react to form fist and marble sized hard clumps, called clinker. Pyroprocessing is an energy intensive process. The amount of energy needed depends on the moisture content of the raw materials and the oven type used. For the heating of the rotating ovens, coal, fuel oil, natural gas or waste material can be used. In special cases, water is used for cooling of the clinker [37].

In the last processing step, the clinker from pyroprocessing is mixed with approximately 4% gypsum and is ground to Portland cement. The grinding of the clinker requires a large amount of electricity. Since the production of clinker by pyroprocessing and grinding is such an energy intensive process, other additives can be used to reduce the amount of clinker in cement and to change cement properties. An example of a clinker substitute is blast furnace slag, a waste product from steel production [37].

### 2.3. Glass

Glass usually refers to silicate glass, a substance containing a high proportion of silica ( $\text{SiO}_2$ ) that forms glass after cooling from its molten state. Glass is produced in many forms and used for many purposes. It includes four main categories: (i) container glass; (ii) flat glass; (iii) fibre glass; and (iv) specialty glass. Glass production is dominated by container glass and flat glass. The construction industry is very important for the glass industry, since flat glass is applied in new buildings and for replacing old glass [36]. In 2009, the global market demand for flat glass was 52 Mt [31]. Fig. 3 shows the flat glass production chain, including three main steps: (1) extraction and processing of raw materials; (2) melting; and (3) annealing and cutting.

In the first step, most raw materials are extracted from mines or quarries. Appendix I in the Supporting Information (SI) shows a typical composition of flat glass, mainly silica sand, soda ash, limestone and often cullet, recycled glass or waste glass from manufacturing [33]. Usually, the cullet used for flat glass is from internal origin, such as from cuttings and breakages. Before reuse, the cullet is ground and washed [9]. In some places in the world, soda ash is mined, but it can also be chemically produced by the so called Solvay process. The Solvay process needs large amounts of water for cooling, washing and as medium for the chemical process [22].

In the second step, the melting step, the mixture that results after grinding and mixing is heated in a furnace. At temperatures between 1300 and 2000 °C, depending on the type of glass, the mixture is melted and becomes liquid glass. By chemical reactions, silicate bonds are created and gas is emitted [9,36]. Furnaces are in most cases heated by natural gas or fuel oil, rarely by electricity. Mostly electricity is used in addition to fossil fuelled glass production [9,33].

The third step includes the annealing and cutting of the material. In the annealing stage, the temperature is lower than in the melting stage. The glass is cooled to 900–1350 °C. At this stage, the impurities are being disposed of and all remaining soluble bubbles are reabsorbed into the melt [36]. Water is used for cooling [19]. After cooling, the glass edges are trimmed and the glass is cut to the desired shape. The edge trimmings and broken glass usually return to the furnace for remelting.

## 3. Method and data

Unalloyed steel contributes 89% of the global steel production [38]. Chromium-nickel steel is the most produced unalloyed steel [20]. Portland cement and Portland composite cement are the two most supplied cement types, accounting for 86% supplied in the EU-25 in 2005 [37]. Soda-lime glass is the most applied glass type, float glass the most produced flat glass [36]. The five end products included in this study are: (i) unalloyed steel; (ii) chromium-nickel alloyed steel (18/8); (iii) Portland cement (CEM I); (iv) Portland

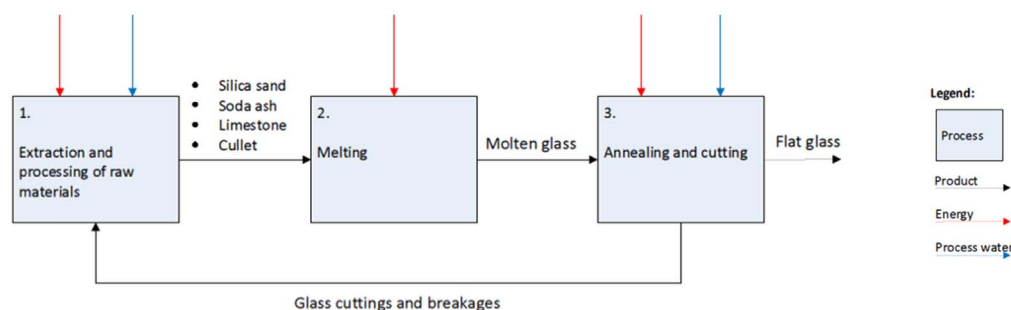


Fig. 3. The flat glass production chain. Every step needs the input of energy (red arrows) and water (blue arrows) and results in the output of products (black arrows). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

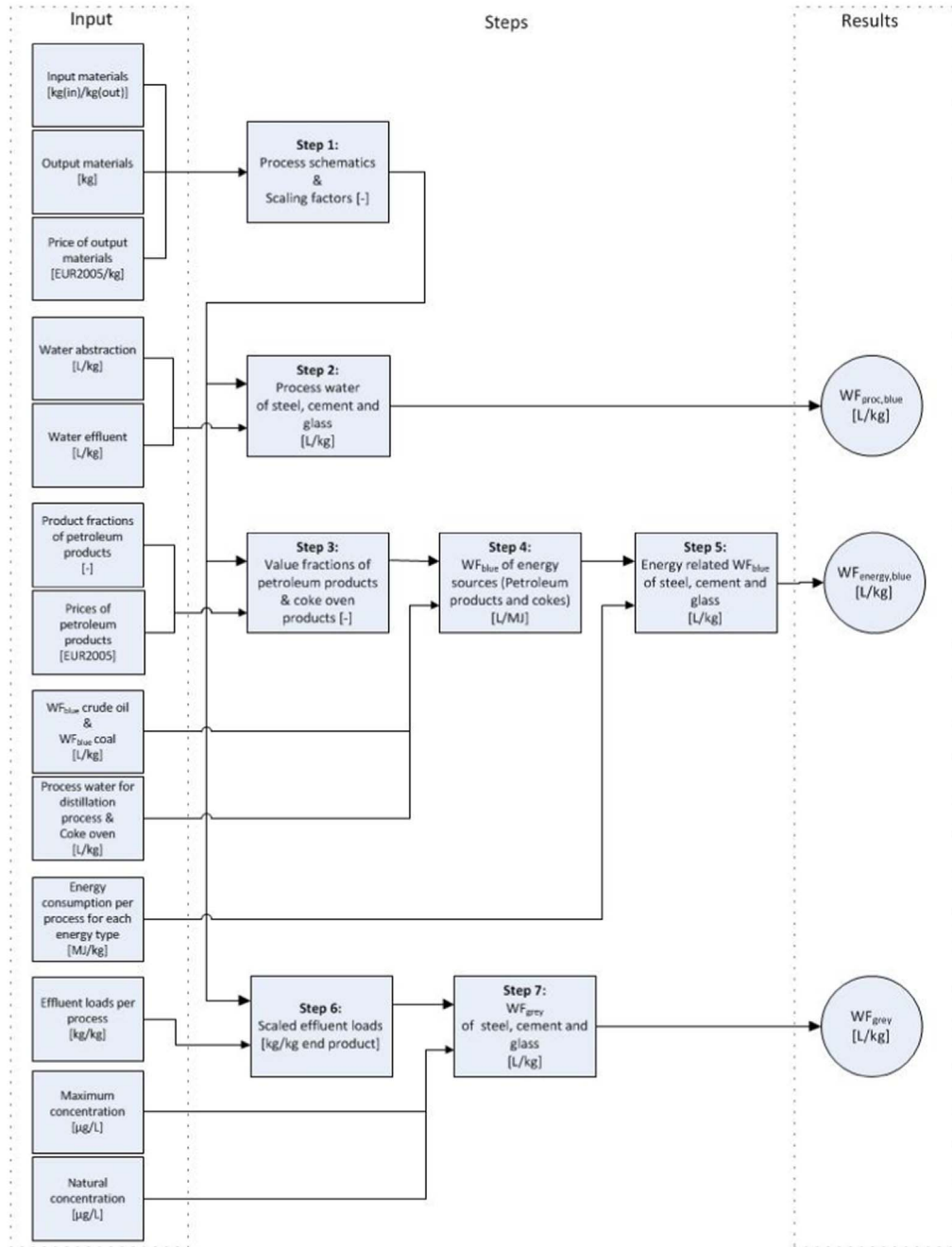


Fig. 4. Steps of the research.

composite cement (CEM II/B); and (v) soda-lime float glass.

The processes in the production chains of these end products require water and energy and often have pollutant effluents. We distinguished between a direct blue WF in each process (WF<sub>proc,blue</sub>) and an indirect blue WF related to the energy input (WF<sub>energy,blue</sub>) that refers to the blue WF in the fuel or electricity supply chain. For each process, we considered the grey WF associated with the pollutants in process wastewater (if applicable). The WFs associated with the process steps were allocated to the end products. Fig. 4 shows the calculation steps.

For many industrial processes, the Ecoinvent 3.2 database specifies input and output materials, by-products and waste products, water abstraction, evaporation and water discharge, energy use and pollutants in effluents [7]. Unless mentioned otherwise, data on inputs-outputs were taken from the Ecoinvent database 3.2 using global (GLO) datasets. Data on energy and water use were taken from OECD and IEA [33] and from JRC [21–24]. To compare Ecoinvent 3.2 data with independent sources, we used Remus et al. [35]



for steel, Scalet et al. [36] for glass and Schorcht et al. [37] for cement.

In step 1 of the research, we drew the process schematics and assessed the scaling factors for unalloyed steel, chromium-nickel alloyed steel, Portland cement, Portland composite cement and soda-lime float glass (SI Appendix II). A scaling factor scales each process to yield the amount of intermediate product required for one kilogram of end product, the functional unit. We used the LCA software program GaBi [13] to build process schematics based on production chains. We used the program to keep track of the product flows between processes and to scale the processes to the end product output amounts. In case a single process has multiple output products, water and energy consumption and pollution were allocated over the output products following the method commonly applied in both LCA and WFA studies [18]. The value fraction ( $f_v$ ) of an output product (p) is defined as the ratio of its market value and the aggregated market value of all output products (p = 1 to z) obtained from the input products [18]. We allocated according to the value fractions of the output products:

$$f_v[p] = \frac{\text{price}[p] \times w[p]}{\sum_i^z (\text{price}[p] \times w[p])} [-] \quad (1)$$

Both purposes are combined by GaBi into one scaling factor. The scaling factor of process i is:

$$f_s[\text{proc}_i] = f_v[p] \times f_w[p] \times f_s[\text{proc}_{i+1}] \quad (2)$$

In which  $f_v[p]$  is the value fraction of product p,  $f_w[p]$  is the ratio between the weight of the input product [p] for process ( $\text{proc}_{i+1}$ ) and the weight of the same product [p] as output from the process ( $\text{proc}_i$ );  $f_s[\text{proc}_{i+1}]$  is the scaling factor of the process i + 1.

In step 2 we estimated the blue WF per production process and the aggregate for each of our end products. The process blue WF ( $WF_{\text{proc},\text{blue}}$ ) is the amount of fresh water that does not return to the same catchment within the same time period, either by evaporation, incorporation into the product or because it is returned to another catchment or in another time period [18]. We calculated the blue WF per process using water abstraction and discharge data per production process (l/kg end product). We assumed that the process blue WF is the difference between abstraction and discharge. By multiplying by the corresponding scaling factor, we calculated the process blue WFs of the end products steel, cement and glass as:

$$WF_{\text{proc},\text{blue}} = (\text{Abstraction} - \text{Discharge}) \times f_s[\text{volume/mass}] \quad (3)$$

SI Appendix III gives data on process water per production process.

Many industrial processes use energy in the form of electricity or heat. Heat can be generated through the burning of natural gas, fuel oil, coal or hard coal cokes. To calculate the WF of steel, cement and glass, we also included the WF of energy. In step 3, we calculated the value fractions of petroleum products and hard coal cokes. We used data on global weighted average WFs of electricity, natural gas and coal from Mekonnen et al. [26]. Heavy and light fuel oil and diesel are petroleum products derived from crude oil. Using Eq. (1), we calculated the value fractions ( $f_v$ ) of the petroleum products (p) and of the products from coking. Table A8 in Appendix IV of the SI shows the value fractions of the petroleum products. Table A9 in SI Appendix IV shows the value fractions of hard coal cokes and the other output products from coking.

In step 4, we assessed the blue WF of the energy sources. Based on the value fractions from step 3, we calculate the blue WF of diesel, light fuel oil, heavy fuel oil and hard coal cokes as follows:

$$WF_{\text{prod}}[p] = \left( \frac{WF_{\text{proc}}[i]}{f_p[p, i]} + \sum_{i=1}^y \frac{WF_{\text{prod}}[i]}{f_p[p, i]} \right) \times f_v[p][\text{volume/mass}] \quad (4)$$

For the distillation process of crude oil and coking of hard coal, the process WF is given per unit of input product, the given volume needs to be divided by the product fraction for that input product ( $f_p[p, i]$ ). The WF of conventional oil ranges from 7.8 – 212 l/GJ heat [26]. For the calculation of the WF of derived products, we used the median value of 20 l/GJ. Data on the WF of refining of petroleum products of 1.53 l/l crude oil were taken from Wu and Chiu [48]. The largest part is used for cooling. For hard coal, Mekonnen et al. [26] have given a blue WF of 6.6 – 228 l/GJ, with a median value of 15 l/GJ, which we used for the calculation of the WF of hard coal cokes. Ecoinvent 3.2 reports 0.0489 MJ of electricity use and 0.62 l of water evaporation for the process of coking with 1.38 kg of hard coal as input. Table 1 shows the ranges and median value of the blue WF of the energy sources we used in the production processes of steel, cement and glass. The blue WF from natural gas, coal and electricity were taken from Mekonnen et al. [26]. We calculated the blue WF for diesel, light fuel oil, heavy fuel oil and hard coal cokes. Appendix IV in the SI shows the blue WF of the other petroleum and coking products.

In step 5, we calculated the energy-related blue WF ( $WF_{\text{energy},\text{blue}}$ ), defined as the blue WF of the energy consumed for the production of the end product. Appendix V in the SI gives the energy consumption for the production processes of steel, cement and glass. The third column shows the energy input per unit product (MJ/kg) from Ecoinvent 3.2 (2015). To assess the energy consumption per kg end product, we multiplied these values by the corresponding scaling factor from step 1, giving the  $WF_{\text{energy},\text{blue}}$  per process.

In step 6, we scaled the effluent loads per process, using the scaling factors from step one, giving effluent loads, substance loads, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (kg/kg end product). For different substances, the Ecoinvent 3.2 database provides effluent loads (kg/mass output material). Appendix VI in the SI gives the scaled effluent loads per process.

In step 7 we applied the loads from the previous step to calculate the grey WF ( $WF_{\text{grey}}$ ) of the end products per polluting substance for all individual processes by dividing the scaled load of a substance by the assimilation capacity of the water body, calculated as the

**Table 1**  
Ranges and median value of the blue water footprint of energy sources.

Product	WF <sub>blue</sub> range [l/GJ] <sup>a</sup>	WF <sub>blue</sub> median value [l/GJ]
Diesel	28 – 376	80
Light fuel oil	19 – 259	55
Heavy fuel oil	10 – 133	28
Natural gas	0.6 – 18	2.2
Coal <sup>b</sup>	6.6 – 228	15 – 39
Hard coal cokes <sup>c</sup>	42 – 321	52 – 82
Electricity	4241	

<sup>a</sup> The numbers between brackets of petroleum refined products are calculated with the median value for the fuel supply from Mekonnen et al. [26] and the mean value from the water consumption in the petroleum refinery from Wu and Chiu [48]. The range is calculated using the range for oil and coal supply from Mekonnen et al. [26] and the range for process water use for distillation by Wu and Chiu [48].

<sup>b</sup> 15 l/GJ is from Mekonnen et al. [26]. 39 l/GJ coal is calculated using Ecoinvent data. The number includes electricity use and may be responsible for the increase in WF<sub>blue</sub> for coal.

<sup>c</sup> 52 l/GJ HCC when 15 l/GJ for coal is used; 82 l/GJ HCC when 39 l/GJ for coal is used.

difference between the maximum allowable concentration and the natural concentration [18]:

$$WF_{grey} = \frac{L}{c_{max} - c_{nat}} [\text{volume/mass}] \quad (5)$$

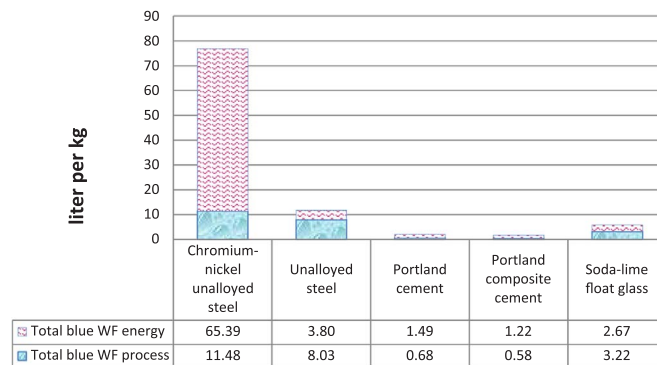
Data on natural concentrations were taken from Chapman [4]. The grey WF manual [12] recommends using these values when local natural background concentrations cannot be used. For the maximum allowable concentrations, we derived data from Franke et al. [12] and used the lowest concentration for Canada, Europe (EU) and the United States. We took data on maximum concentrations for COD and BOD from the EEC [8] guideline.

The Solvay process is the process of chemically producing soda ash. According ESAPA [10], hydroxide is present in the effluent of this process. The association does not set a maximum concentration for hydroxide. However, the CCME guideline advises a pH range of 6.5 – 9 [12]. In order to calculate the grey WF for hydroxide ions, we adapted Eq. (5) to express the concentration  $c_{max}$  and  $c_{nat}$  in a pH (see Appendix X in the SI).

#### 4. Results

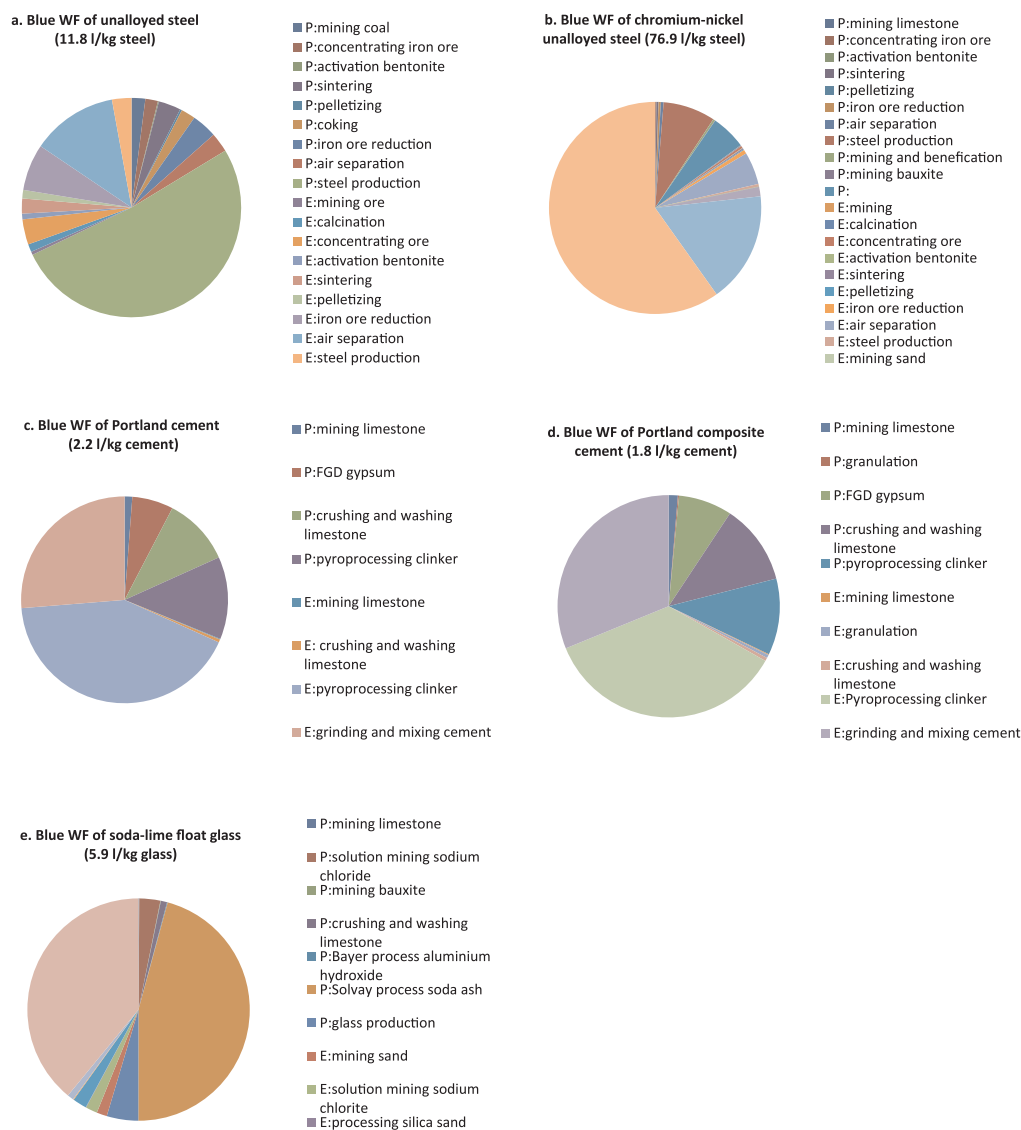
Fig. 5 shows the blue WFs of chromium-nickel unalloyed steel, unalloyed steel, Portland cement, Portland composite cement and soda-lime glass for the production process and for the energy related to the production process. The blue WF for the process (l/kg) is largest for steel and relatively small for cement. The WF of glass finds itself in between the two extremes. For steel, the blue process WF of chromium-nickel unalloyed steel is 43% larger than the blue WF of unalloyed steel. For cement, the blue process WF of Portland cement is 17% larger than the blue WF of Portland composite cement. Especially the blue WF of energy of chromium-nickel unalloyed steel is relatively large, six times the blue WF of the process to produce the steel. For unalloyed steel, the blue WF of energy is only half the blue WF of the process. For cement, the blue WF of energy is two times the blue WF of the process, for glass the values are about the same.

Fig. 6 shows how the different processes of the supply chain contribute to the five end products considered. A distinction is made between direct water use in production processes (P) and indirect water use for producing the energy used in production processes (E). For unalloyed steel, the blue WF of 11.8 l/kg is dominated by the blue WF of energy needed for pelletizing (52%), followed by the

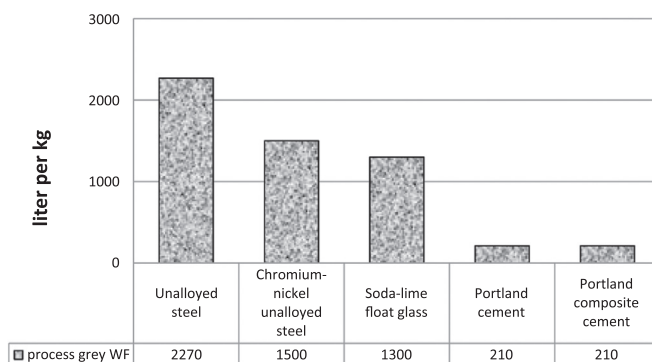


**Fig. 5.** Blue WFs of chromium-nickel unalloyed steel, unalloyed steel, Portland cement, Portland composite cement and soda-lime glass for the production process and for the energy related to the production process.





**Fig. 6.** The contribution of different processes to the blue WF of unalloyed steel (a), chromium-nickel unalloyed steel (b), Portland cement (c), Portland composite cement (d), and soda-lime glass (e). A distinction is made between direct water use in production processes (P) and indirect water use for producing the energy used in production processes (E).



**Fig. 7.** Grey WF of the production process of unalloyed steel, chromium-nickel unalloyed steel, soda-lime glass, Portland cement, and Portland composite cement.

blue WF of energy needed for air separation and iron ore reduction (7%). For chromium-nickel unalloyed steel, the blue WF of 76.9 l/kg is dominated by the blue WF of energy needed for mining of ferronickel (60%), followed by the blue WF of energy for the pre-treatment of ferrochromium (17%) and the WF related to the production of steel (8%). For Portland cement, the blue WF of 2.2 l/kg is dominated by the blue WF of energy needed for pyroprocessing of clinker (26%), followed by the blue WF of energy for grinding and mixing of cement (26%) and the blue WF of the grinding and mixing of cement (13%). For Portland composite cement, the blue WF of 1.8 l/kg is also dominated by the blue WF of energy needed for pyroprocessing of clinker (36%), followed by the blue WF of the energy for grinding and mixing of cement (31%) and the blue WF of the crushing and washing limestone (12%). For soda-lime glass, the blue WF of 5.9 l/kg is dominated by the blue WF of the Solvay process to make soda ash (46%) and the blue WF of the energy for glass production (36%).

Fig. 7 shows the grey WFs of chromium-nickel unalloyed steel, unalloyed steel, Portland cement, Portland composite cement and soda-lime glass for the production process. Unalloyed steel has the largest grey WF, 51% larger than the grey WF of chromium-nickel unalloyed steel. The grey WFs of Portland cement and Portland composite cement are the same. They are a factor of ten smaller than the grey WF of unalloyed steel. The grey WF of soda-lime float glass is 15% smaller than the grey WF of chromium-nickel unalloyed steel and 75% smaller than the grey WF of unalloyed steel. The grey WFs of steel, cement and glass are much larger than the blue WFs. Chromium-nickel unalloyed steel has a relatively large blue WF related to energy and therefore a relatively small grey to blue WF ratio of 20. For Portland cement, the grey to blue WF ratio is 97, for Portland composite cement 117, for unalloyed steel 192 and for soda-lime float glass 221.

The grey WF is calculated per pollutant as the pollutant load divided by the difference between the maximum allowable concentration and the natural concentration for that pollutant. The final grey WF is determined by the critical pollutant, i.e. the one with the largest pollutant-specific grey WF. For unalloyed steel and for chromium-nickel alloyed steel, the cadmium concentration determines the grey WF (see SI Appendix IX, Figs. A14 and A17). For Portland cement and Portland composite cement, mercury is the critical pollutant (see SI Appendix IX, Figs. A20 and A23). For glass, the grey WF is determined by suspended solids (see SI Appendix IX, Fig. A26).

## 5. Discussion

For the first time, this study uses LCA software and databases to estimate blue and grey WFs of products, showing that methods, tools and data from both fields can effectively be combined. The inventory of all processes in a production chain and estimation of water consumption and pollution per link in the chain enable the assessment of the WFs of the end products and the identification of where in the chain the largest water consumption and pollution take place.

The study focused on the production of construction materials, excluding transportation. If the materials needed for the production process are mined and processed in different locations, transportation is needed, requiring energy that has a WF. Depending on the transport mode, energy source and distance, there is an additional energy requirement (that also has a WF) that needs to be taken into account. However, the energy requirement of transportation is small compared to the production processes and varies between 0.09 MJ per 1000 kg/km for transport by ship over sea to 2.9 MJ per 1000 kg/km for transportation by lorry [14].

The Ecoinvent database 3.2 has been an important source for process data. When working with large compiled datasets, errors cannot be excluded with full certainty. At the time of consulting the database, the cryogenic air separation for liquid oxygen contained an error, reporting an evaporation of 860 l/kg liquid oxygen. Ecoinvent is currently working on reconsidering this number. For this research, we used the much smaller value of 2.7 l/kg liquid from Althaus et al. [1] that is based on the cooling water for an average produced waste heat amount. The products from cryogenic air separation are: 1 kg oxygen, 3.27 kg nitrogen and 0.06 kg argon, resulting in a water consumption of 11.7 l/kg liquid oxygen. The accuracy of this value can also be questioned, because it is not specific for this process, but shows the order of magnitude difference between the reported values.

The applied Ecoinvent 3.2 database specifies input and output materials, by-products and waste products, water abstraction, evaporation and water discharge, energy use and pollutants in effluents [7]. Data on inputs-outputs were taken from the database using global (GLO) datasets. This means that the database gives global average numbers, thus averaging over industries with higher than average effluent loads in their wastewater and industries using best practices.

We used the global weighted average WF of electricity from Mekonnen et al. [26]. However, WFs for electricity for a specific location may differ from the global average value. For example, some integrated steel plants generate their own electric power from off gasses [35]. Other steel plants are located in areas where the energy mix used for electricity generation substantially differs from the global average. Several plants use salt water instead of freshwater for cooling. This can have an effect on the estimated WF, since some forms of energy (e.g. electricity from wind or photovoltaics, geothermal energy) have a much smaller WF than other forms of energy (e.g. energy from fossil fuels, firewood, or hydropower) [26] and the WF of using salt water is zero by definition.

The data from Ecoinvent used for ferronickel is probably not accurate when the impact of ferronickel is large. The data for nickel are based on a study of the energy and material streams from the production of class I nickel. The lacking data mainly concern process specific emissions [5]. The dataset is designed for the use of the metal as raw material in the manufacturing of stainless steels and alloys, as has been done in this study. However, Classen [5] mentions that when the impact of ferronickel is high, the data should not be used. We derived lacking data from similar processes for copper winning, assuming the processes are similar. This leads to an estimation of the WF of ferronickel and thus of chromium-nickel alloyed steel. The relatively large electricity use of melting ferro-nickel influences the blue WF of chromium-nickel alloyed steel. However, the grey WF of ferronickel is not critical for the grey WF of chromium-nickel steel. Furthermore, Ecoinvent did not report process water consumption for the production of ferronickel, but JRC [24] reports 6.9 m<sup>3</sup>/t water consumption for ferroalloys in general, although not specifically for ferronickel. The water uses are for

wet off-gas cleaning, slag granulation and cooling.

Most data on energy consumption from OECD/IEA, JRC and Ecoinvent 3.2 are similar. However, for the energy consumption of clinker production, the energy consumption reported by Ecoinvent is lower than that of OECD and IEA [34]: 2 MJ/kg (excluding waste products as fuel) versus 2.9 – 6.7 MJ/kg (depending on the production process and kiln technology). The difference can partly be attributed to the fact that Ecoinvent lists waste products used as fuel but these are not included in the reported 2 MJ/kg. The WF related to energy from waste falls outside the system boundary of this research.

Another issue regarding energy consumption data occurs for the case of the fuel distribution for glass melting. Ecoinvent mentions the following distribution: 58% natural gas, 38% heavy fuel oil and 5% electrical power. According to Scalet et al. [36], an electrical boost of 10% is not uncommon. Since electrical power consumption has a large influence on the blue WF, the blue WF using 10% electrical boost would be 4.0 l/kg glass instead of 2.2 l/kg glass. Appendix VII in the SI shows the energy-related WF of float glass with other energy distributions.

For float glass, there are three alternative production possibilities. For the calculation of the WF, these possibilities were not taken into account. For the Solvay process, we assumed the use of freshwater. ESAPA [10] mentions that for brine production, it is possible to use seawater. When seawater is used, the WF of the Solvay process is much smaller than calculated in here, as the brine production is a large water requiring process [10]. We also excluded the alternative dry lime process instead of the usual use of liquid of lime. This might reduce water consumption of the soda ash production. Furthermore, no quantitative data were available on soda ash mining. The WF of float glass using soda ash from mining is smaller than that of float glass using soda ash from the Solvay process. We did not calculate the WF of glass with natural sources of soda due to a lack of data.

The use of supplementary materials as clinker substitutes in cement production reduces greenhouse gas emissions [11,25]. Our results suggest that using clinker substitutes to produce Portland composite cement instead of Portland cement also reduces the WF related to the energy consumption for pyroprocessing. Crossin [6] notes that the reduction of greenhouse gas emissions by using ground granulated blast furnace slag (GGBFS) depends on the definition of a byproduct. If a byproduct is defined as a waste, this affects the allocation and the processes included in the analysis. The same argument applies for the WF of cement and other by-products used as supplementary materials, such as fly ash or gypsum from flue gas desulphurisation (FGD). It can be argued that the WF from FGD should not be allocated to cement but to power generation, since this is a process to clean flue gas from power generation. When this process is not allocated to gypsum and cement production, the grey WF will be much lower. The clinker production then results in a grey WF for the substance cadmium of 0.63 l/kg Portland cement and 0.45 l/kg Portland composite cement.

The results of the grey WF should be interpreted cautiously, as the wastewater is not always specified as emitted to the environment. It is unclear whether all effluent loads reported by the Ecoinvent database are emitted to the environment. We assumed here that Ecoinvent gives the effluent loads after the process of wastewater treatment, i.e. the actual loads to the environment. In cases whereby wastewater is treated such that the loads reported by Ecoinvent are actually too high, we will have overestimated the grey WF. Furthermore, the application of the grey WF concept implies that we have quantified the amount of water needed to dilute the chemical loads entering the water to accepted water quality standards. We did not consider the fate of pollutants once entered into the water.

Cadmium in the effluent of especially iron ore processing activities results in the largest grey WF of all reported substances. Low levels of maximum allowable concentrations for cadmium are a cause of the large grey WF. Prevention from entering the environment by reducing the load in the effluent may reduce the grey WF of iron and steel. WQA [47] lists the following six treatment methods for reducing cadmium: (i) strong acid cation resin; (ii) weak acid cation resin; (iii) reverse osmosis; (iv) distillation; (v) precipitation/filtration and (vi) lime softening. JRC [23] mentions several best available techniques to reduce emissions to water, specifically for mining activities. The method discussed by JRC [23] to remove dissolved metals uses the adsorption ability of finely ground tailings. Water treatment by precipitation for which sulphide or lime or a combination is used is also mentioned.

When we compare our results with results from the case study for Tata steel in India [39] there are some differences. We calculated a blue WF for steel ranging between 11 l/kg (unalloyed steel) and 77 l/kg (chromium-nickel unalloyed steel), where Unger et al. [39] find a value of 4.2 l/kg steel. We find that for steel, the critical pollutant is cadmium; the Tata study indicates that suspended solids are the critical pollutant. Our results show a blue WF for cement between 1.7 and 2.6 l/kg. The Tata study finds a slightly higher value of 3.3 l/kg. The comparison shows that in order to make a database for industrial products, more case studies are needed.

## 6. Conclusion

For chromium-nickel unalloyed steel, unalloyed steel, Portland cement (CEM I), Portland composite cement (CEM II/B) and soda-lime glass, the WF is dominated by the grey WF, which is a factor of 20–220 larger than the blue WF. Chromium-nickel alloyed steel (18/8) has a blue WF of 77 l/kg and a grey WF of 1500 l/kg, with cadmium as the critical pollutant. Unalloyed steel has a blue WF of 11 l/kg and a grey WF of 2300 l/kg, with again cadmium as the critical pollutant. Unalloyed steel has a much smaller blue WF than chromium-nickel alloyed steel. The ferroalloys are produced in electric arc furnaces, which increases the blue WF related to electricity use. However, the grey WF of unalloyed steel is smaller than that of chromium-nickel alloyed steel. Beneficiation of iron ore has the largest influence on the grey WF. The use of ferroalloys in alloyed steel reduces the factor of beneficiation (i.e. concentrating, sintering and pelletizing) of iron ore in steel making. The production of ferroalloys adds to the grey WF of alloyed steel, however not as much as the grey WF is reduced by using less iron ore. After cadmium, copper and mercury are the critical pollutants for the grey WF.

Portland cement (CEM I) has a blue WF of 2.0–2.6 l/kg, depending on the source of gypsum. The grey WF is 210 l/kg, determined by mercury if gypsum from flue gas desulphurisation is used for the production. Without the use of gypsum, the grey WF is 0.63 l/kg, with cadmium as the critical pollutant. Portland composite cement (CEM II/B) has a blue WF of 1.7–2.1 l/kg. The grey WF is 210 l/kg, with mercury as the dominant pollutant if gypsum from flue gas desulphurisation is used. Without gypsum from flue gas desulphurisation, the grey WF is 0.45 l/kg, determined by cadmium. Portland cement has a larger WF than Portland composite cement. Clinker production by pyroprocessing contributes most to the blue WF, due to high energy consumption. The use of supplementary materials to substitute clinker reduces the WF of cement. Gypsum production from flue gas desulphurisation causes the largest grey WF of 210 l/kg cement determined by mercury. From a WF point of view, it would be better to use Portland composite cement (CEM II/B) instead of Portland cement (CEM I) if both types of cement have the right properties for the circumstances in which it is used.

Soda-lime float glass has a blue WF of 5.8 l/kg. This is for glass that includes soda ash from the Solvay process. The grey WF of float glass is 1300 l/kg, with suspended solids as the critical pollutant. Soda ash produced by the Solvay process has a large influence on both the blue and grey WF of float glass. The Solvay process requires a large amount of water, while the effluent of the Solvay process contains high concentrations of heavy metals, suspended solids and can have a high pH value.

The blue WF related to energy consumption is a significant part of the total blue WF of chromium-nickel unalloyed steel, unalloyed steel, Portland cement, Portland composite cement and soda-lime glass. The production of these materials is energy demanding and includes large electricity use. The WF of electricity is large compared to other energy sources, like heat. We showed that the energy-related blue WF is dominated by electricity use. When electricity production moves towards energy sources with a comparatively small WF (e.g. solar, wind and geothermal energy), the WF of the electricity-related WFs of construction materials can be substantially reduced.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.wri.2017.11.002>.

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